A "Twisted-Mode" Technique for Obtaining Axially Uniform Energy Density in a Laser Cavity

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Ruby lasers generally oscillate simultaneously in several axial modes,[1] despite the fact that the atomic transition involved in the laser action is homogeneously broadened. According to present explanations,[2] such simultaneous oscillations can occur because different axial modes have different longitudinal standing-wave patterns and energy distributions, so that different axial modes in essence make use of different regions of the ruby rod. As a consequence, one prescription for achieving single-axial-mode operation in ruby is believed to be the use of a mode pattern which produces spatially uniform energy density and saturation throughout the ruby volume, for example, a running-wave mode in a ring laser.[2]

We outline in this note a method for achieving a standing wave with an axially uniform energy density in a laser cavity. The axial modes of an ordinary laser cavity have a twofold polarization degeneracy. This is usually not of interest in ruby, since only one polarization oscillates due to the selection rules for the atomic transition. However, it is possible to excite two orthogonal polarizations in such a way that axially uniform energy density is obtained. This can be done by placing a birefringent element, specifically a quarter-wave plate, at each end of the laser cavity between the rod end and the mirror. It is believed that the axial uniform saturation will in turn cause the rod to oscillate in a single axial mode only.

Figure 1 shows the physical configuration envisioned. The 0° ruby rod (c axis along rod axis) will exhibit no birefringence (if its quality is sufficiently high), and the laser transition will be equally stimulated by any transverse polarization of the optical electrical field. The rod axis is the z axis. The end sections are birefringent quarter-wave plates, which conveniently may be made of sapphire; and the principal axes x', y' and x'', y'' of these birefringent sections are rotated by an angle α with respect to each other, as shown. Among the important properties of this configuration are:

(1) The normal modes (axial modes) of the structure may be viewed as consisting of either right-handed or left-handed circularly polarized waves traveling right and left in the center section. A right-handed circularly polarized wave traveling to the right, say, is reflected from the right end section with the same right-hand sense of circular polarization going in the opposite direction. (Two quarter-wave plates plus a mirror reflection equal a full-wave plate.) After reflecting in the same fashion off the left end section the wave still has its original right-hand polarization and can "catch its tail" to complete the mode.

(2) Summing the right-going and the left-going right-handed or left-handed circularly polarized waves of a mode gives E_x and E_y standing waves which are spatially displaced with respect to each other by $\lambda/4$, i.e., $E_x \sim \cos(kz + \theta)$ and $E_y \sim \sin(kz + \theta)$. Hence, the total energy density $E_x^2 + E_y^2$ in a mode is uniform along the rod. The E-field mode pattern in the rod at an instant of peak E field has the shape of a twisted ribbon with a spatial period of one optical wavelength. Hence, we refer to this as a "twisted-mode" structure. The standing-wave mode twists in opposite senses depending on whether it arises from right-handed or left-handed polarized running waves.

(3) Let the total electrical length of the center section plus the mean electrical lengths of the two end sections be written as $\phi' = 2\pi L'/\lambda$, thereby defining a mean effective structure length L' for the rod plus end sections. Then, the axial mode frequencies of this structure are given by

$$f_q \approx \left(q \pm \frac{\pi - 2\alpha}{2\pi} \right) \frac{c}{2L'},$$

where q is any integer. The axial mode degeneracy is split symmetrically as indicated in Fig. 1. The (+) and (−) modes represent right-handed or left-handed circularly polarized waves, i.e., the alternate (+) and (−) modes have ribbon patterns twisting in opposite directions. To put this another way, a circularly polarized wave making a round trip has a slightly longer or shorter trip depending on whether it rotates with or against the relative rotations of the end sections. Therefore, the right-handed and left-handed modes are separated in frequency.

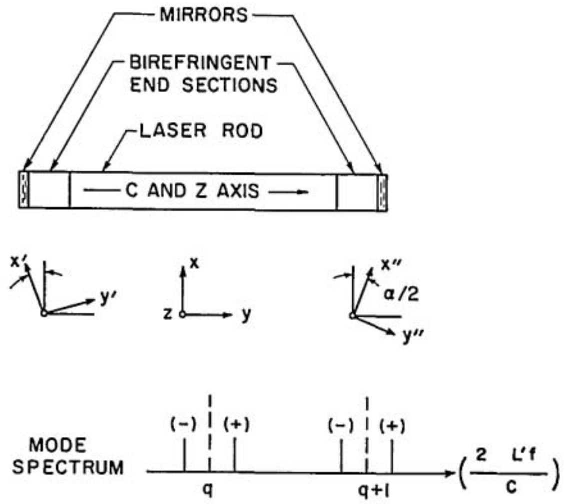

Fig. 1. Construction and mode spectrum of a "twisted-mode" laser resonator.

(4) The polarizations of the right-handed and left-handed twisted modes at the end faces (i.e., at the mirrors) are linear polarizations oriented at 90° to each other and at 45° to the principal axes of the end sections. Therefore, the output of the laser will be linearly polarized, with a 90° rotation between right-handed and left-handed sets. It may be necessary to use a polarizing or dichroic element located just inside an end mirror to eliminate either the right-handed or the left-handed set of modes. Simultaneous excitation of both sets is not desirable since it will destroy the uniformity of the energy density in the active material.

The above discussion has been for a laser of an arbitrary angle α between the axes of the quarter-wave plates. It should be noted, however, that there are two special cases of particular interest: (1) $\alpha = 45°$.[3] In this case the frequency splitting between the right-handed and left-handed modes is maximum and is equal to one-half the spacing between the modes of a resonator with optical length equal to L'. (2) $\alpha = 90°$. In this case the right-handed and left-handed modes are degenerate in frequency. It is convenient in this case to consider two orthogonal plane polarizations (rather than circular) with $\mathbf{E}$ vectors along the axes of the birefringent plates. The standing-wave patterns corresponding to these two polarizations and having the same resonant frequency are then seen to be spatially displaced inside the active material by $\lambda/4$ with respect to each other, thus resulting in a uniform energy density in the material. The polarizers placed between the birefringent plates and resonator reflectors, as mentioned above, may in this case be looked upon as ensuring equal excitation of the two linear polarizations which, of course, is necessary for the successful operation of the device. A complete analysis of the more general case of arbitrary wave end sections with arbitrary rotations has also been carried out. Experimental tests of this concept are now in progress, and will be reported upon when completed.

The axial mode control technique described here was independently conceived by V. Evtuhov in December 1963, in the course of research supported by a contract from the U.S. Air Force, Wright-Patterson Air Force Base, Ohio; and by A. E. Siegman in June 1964, under the support of a contract from the U.S. Army Electronics Command, Fort Monmouth, N.J.

Note added in proof. Preliminary experiments conducted at Hughes Research Laboratories using the "twisted mode" technique with $\alpha = 90°$ have resulted in single-mode operation of a ruby laser under certain circumstances. Appropriate quarter-wave plates (actually 7 $\lambda/4$ plates) of sapphire were cut, polished and attached to the ends of an accurately oriented 0°, 3 mm diam, 2.54 cm long ruby rod, with the help of butyl methacrylate cement. Silver reflectors were then evaporated on the quarter-wave plates, and transverse mode selection was performed. The assembly was pumped in a double-elliptical cavity, and the spectrum of the output was examined using a Twyman-Green interferometer. For certain azimuthal orientations of the assembly in the pumping cavity, single-frequency output was observed at pumping levels of up to ~15% above threshold. The reasons for azimuthal dependence of the spectrum are not yet clear, although some possible explanations are being examined.

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High-Resolution X-Ray Collimator with Broad Field of View for Astronomical Use

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Several x-ray sources of extraterrestrial origin have been found by rocket observations.[1-3] In these observations Geiger counters and proportional counters with limited fields of view have been used as detectors. The accuracy of a measurement of the angular size of a source is limited by the angular width of the field of view of the detector which has been typically several degrees. This angular width cannot be made very small in experiments from spinning platforms because of the low quantum intensities of the sources.

A collimator has been designed which permits greatly increased accuracy in the measurement of the angular size of the x-ray sources while using detectors with wide fields of view. The basic idea of the collimator is illustrated in Fig. 1. The collimator is composed of two identical grids which are made with wires of each diameter, d, and separations between wires are S each. The grids are separated by D. If the angular size of the source δ is much smaller than d/D rad, the two grids altogether are transparent or opaque to the source depending upon whether the shadow of wires of the front grid is on the wires or the gaps between wires of the rear grid. Therefore, the radiation flux through the two grids is modulated while the direction of the source with respect to the collimator moves, with the frequency which can be predicted by means of the design of the collimator and the movement of the relative direction of the source.

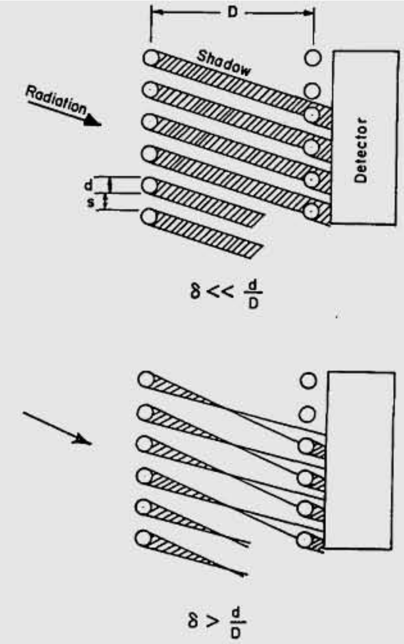

Fig. 1. Schematic diagram showing the collimator's principle.

If, on the other hand, the angular size of the source is much larger than d/D rad, the shadow of the front grid at the rear grid is not clear and the flux is not modulated by the collimator. If the source is about as large as d/D rad, the flux will be partly modulated. Thus, the magnitude of the modulation of the flux while the source is in the field of view will tell us the size of the source.

Typical dimensions of a collimator which has been employed in rocket x-ray experiments are as follows: $d = 0.2$ mm, $S = 0.2$ mm, $D = 3.8$ cm, total area ≈ 12.7 cm $\times$ 15.2 cm, and resolution ≈ 10 arc min. It is not impractical to design the collimator of the resolution of one arc min.

The special virtue of this collimator is that the total flux of x rays detected while the source is in the field of view is essentially independent of the angular resolution regardless of how fine a resolution is required.

The collimator has been used for the purpose of x-ray astronomy so far, but may find more general use in the determination of the angular size of a source of any soft radiation like ultraviolet light, infrared light, and corpuscular streams, when the direction of source is known approximately, but the flux is not strong enough to permit one to narrow the field of view of the detector and then scan the region of the source.

G. Clark, G. Garmire, and M. Wada of MIT participated in developing this collimator. This collimator has been used for rocket x-ray observations in collaboration with R. Giacconi, H. Gursky, and J. Waters, of American Science and Engineering, Inc.

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